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Phasing of independent laser channels under impact SBS excitation

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Abstract. **It is shown experimentally that phasing of independent laser channels under impact SBS excitation calls for a stable difference in arm lengths, as in a classical Michelson interferometer. A scheme with automatic compensation for fluctuations of interferometer arm lengths has been proposed and experimentally implemented. This scheme makes it possible to perform stable phasing of two laser channels under standard laboratory conditions.**

Keywords: *phasing of independent laser channels, impact SBS excitation, interferometric technique.*

Phasing of independent laser channels is of great interest for researchers, because this technique provides high-power laser radiation with conservation of high optical quality of the entire beam. Most experimental studies in this field were devoted to the phasing of cw single-mode fibre lasers (see, e.g., [1–3]). The reason is that one can install an independent phase modulator in each channel in these systems and control the phase of each channel using feedback circuits. Here, the main problem is to develop efficient algorithms for comparing phases of different channels and provide a sufficiently high operating speed of feedback circuits. According to the experiments performed in [1–3], the operating speed of these phase control systems ranges from several tens of milliseconds to several tens of microseconds. Hence, they cannot be applied to nanosecond laser systems.

When studying the laser beam phase conjugation, several methods have been proposed for phasing pulsed laser channels [4, 5]. Their main drawback was the necessity of converging beams in all channels into one active volume for mutual phasing. This circumstance limited the number of channels used for phasing. Nevertheless, nine pulsed channels were experimentally phased in [5].

A method for phasing independent pulsed laser channels was proposed and experimentally realised by Lee et al. [6] in 2005. Although being implemented in practice for two channels, it in essence allows for scaling to an arbitrary number of channels. Then, based on the proposed approach, these researchers published a series of studies, where projects of high-power laser systems for laser fusion were described [7–9]. However, the necessary conditions for implementing the aforementioned phasing method in high-power laser systems may differ significantly from those considered in [6]. The purpose of our study was to analyse the domain of applicability of this method for phasing independent channels and the factors that may hinder its application in high-power laser systems.

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In our opinion, authors' interpretation of the effect investigated in [6–9] is incomplete and unconvincing. Therefore, we theoretically analysed this problem and found that the physical mechanism of wave phasing is impact excitation of stimulated Brillouin scattering (SBS) [10]. This process is schematically shown in Fig. 1. Pump radiation of intensity I_p is passed through a cell containing an active SBS material and then focused back by a spherical mirror (the so-called back-focusing scheme, which was applied in [6]). If the input wave is plane, interference of two plane waves with identical frequencies occurs in the focal-waist region, and a stationary density grating arises in the medium as a result of electrostriction. This grating is nonresonant for SBS and does not affect this process. However, if the pump pulse has a sufficiently short leading edge, along with the formation of a stationary nonresonant grating, impact excitation of two resonant acoustic waves (propagating in opposite directions) occurs. The frequencies and wave vectors of these waves satisfy the SBS resonance conditions for a given medium, and the waves decay with the lifetime of the corresponding acoustic phonons.

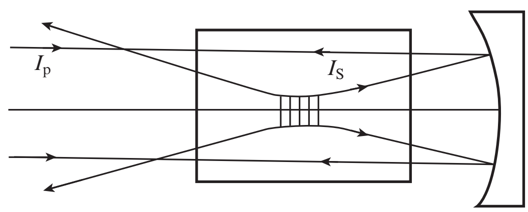

Figure 1. Scheme of an SBS mirror in back-focusing geometry: I_p is the pump intensity and I_S is the Stokes radiation intensity; both pump waves can be considered as plane in the near-focal region.

The phases of these acoustic waves are determined by the phases of plane pump waves. Note that the wave phasing is random and is implemented only when the amplitude of impact-excited acoustic waves exceeds the amplitude of spontaneous acoustic vibrations caused by thermal fluctuations of the medium and having random phases [10].

As the calculations [10] showed, the input laser pulse should have a sufficiently short leading edge, with a width τ_f satisfying the condition $\tau_f \lesssim 3T_2$, where T_2 is the lifetime of acoustic phonons of the medium. In addition, the amplitude of impact-excited acoustic waves should be proportional to $1/(\Omega T_2)$, where Ω is the hypersonic frequency. The critical parameters of widespread active SBS media at the neodymium laser frequency (pump wavelength λ_p = 1.064 μm) are listed in Table 1. It can be seen that, in terms of the first criterion ($\tau_f < 3T_2$), the optimal material is compressed xenon. However, taking into account both critical parameters, a more appropriate medium is Freon FC-75. Note that the experiments [6] were performed with specifically Freon FC-75.

Table 1.

Medium	T_2/ns	Ω/GHz	$1/(\Omega T_2)$
Xe (p = 40 atm)	35	0.32	0.089
CS_2	6.4	3.76	0.042
Acetone	2.0	2.67	0.19
$TiCl_4$	1.5	3	0.22
CCl_4	0.6	2.76	0.6
Freon FC-75	0.9	1.34	0.83

We experimentally investigated the possibility of phasing two independent laser channels. A schematic diagram of the experimental setup is presented in Fig. 2. Input pump radiation with an intensity I_p passes through a polariser (*1*) and Faraday isolator (*2*). The glass plate (*3*) partially reflects the beam to a calorimeter (*4*) (to measure the pump energy) and photodiode (*5*) (to record the pump pulse shape). A semitransparent mirror (*6*) [glass wedge with an apex angle of 2° and deposited dielectric layer (reflectance $R \approx 0.5$) on one side and an antireflective coating on the other side] splits the beam into two beams with equal energies. The transmitted and reflected beams are directed by four glass prisms to a cell (*7*) with an active SBS medium. To obtain absolute identity of the optical properties of phase conjugation mirrors in both channels, the experiments were performed with the same cell. The beams emerging from the cell are focused exactly backward by two concave mirrors [(*8*) and (*9*)]. The focal length of the mirrors was 25 cm, and they were located at a distance of about 8 cm from the cell. The optical path lengths from the semitransparent mirror to the foci of mirrors (*8*) and (*9*) (interferometer arm lengths) were $l_{1,2} = 208 \pm 3$ mm ($\Delta l = l_1 - l_2 \leqslant 0.6$ cm). The shapes of the Stokes pulses formed in the focal waists of the mirrors [(*8*) and (*9*)] and propagating towards their parent focused pump beams were measured by photodiodes (*11*) and (*10*), respectively. The pulses from all photodiodes were applied at the inputs of high-speed digital oscilloscopes.

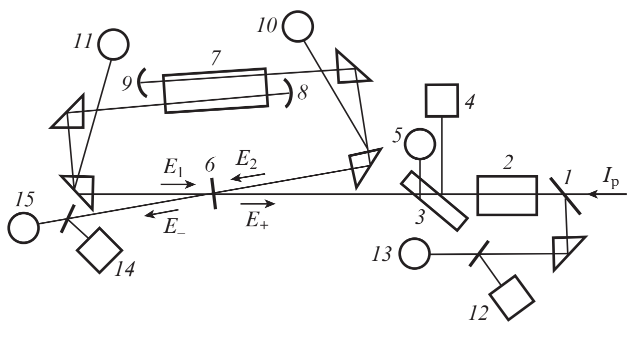

Figure 2. Schematic diagram of the experimental setup: (*1*) polariser; (*2*) Faraday isolator with a 45° quartz plate; (*3*) glass plate; (*4*, *12*, *14*) calorimeters; (*5*, *10*, *11*, *13*, *15*) photodiodes; (*6*) semitransparent mirror; (*7*) cell with an active SBS medium; (*8*, *9*) highly reflecting concave mirrors with a focal length of 250 mm.

Stokes beams with field strengths E_1 and E_2 interfere at mirror (*6*). The interference result is determined by the phase difference $\Delta\varphi$ of these fields. If $\Delta\varphi$ is close to zero, the beams are summed to propagate in the direction of wave E_+, which is opposite to the input pump beam (I_p) direction. When passing through the Faraday isolator, the plane of polarisation is rotated by 90°, and the beam is reflected by the polariser (*1*) to the calorimeter (*12*) and photodiode (*13*). If $\Delta\varphi \approx \pi$, the beams are summed to propagate in the direction of wave E_-, and this summed radiation is measured by the calorimeter (*14*) and photodiode (*15*). The parameter of the in-phase condition for the Stokes beams, determining the proximity of $\Delta\varphi$ to zero, is $\eta = |E_+|^2/(|E_+|^2 + |E_-|^2)$, where $|E_+|^2$ and $|E_-|^2$ are proportional to the beam energies measured by calorimeters (*12*) and (*14*), respectively. Note that the necessary condition for summing the beams from two Stokes channels is the equality of $\Delta\varphi$ to zero or π, depending on the summation scheme. If $\Delta\varphi = 0$, $|E_-|^2 = 0$ and $\eta = 1$. If $\Delta\varphi = \pi$, $|E_+|^2 = 0$ and $\eta = 0$. If phasing is absent in the channels, the division coefficient of the energy reflected by mirror (*6*) changes randomly from pulse to pulse; moreover, experiments revealed that this coefficient may also change within the pulse duration.

To observe directly this dynamics, we developed a technique for measuring the time dependence of the phase difference between the beams reflected in two independent interferometer arms (Fig. 2). The amplitudes of the Stokes waves emerging from the channels of the mirrors [(*8*) and (*9*)] will be denoted as $E_1(t)\exp[i\varphi_1(t)]$ and $E_2(t)\exp[i\varphi_2(t)]$, respectively. Based on the well-known Fresnel formulas for the waves reflected from an interface between two media and transmitted through it (according to which the phase of radiation reflected from a medium with a higher optical density shifts by π, whereas in the case of reflection from a less optically dense medium this shift is zero), we have the following expressions for E_+ and E_-:

$$|E_+(t)|^2 = (1-R)|E_1(t)|^2 + R|E_2(t)|^2$$

$$+2\sqrt{(1-R)|E_1(t)|^2}\sqrt{R|E_2(t)|^2}\cos[\Delta\varphi(t) - 2\pi],$$

$$|E_-(t)|^2 = R|E_1(t)|^2 + (1-R)|E_2(t)|^2$$

$$+2\sqrt{R|E_1(t)|^2}\sqrt{(1-R)|E_2(t)|^2}\cos[\Delta\varphi(t) - \pi],$$

where $\Delta\varphi(t) = \varphi_1(t) - \varphi_2(t)$ and R is the reflectance of mirror (*6*). These expressions are valid for an absorption-loss-free mirror. Note that the pump beam undergoes external reflection from the mirror surface, at which it is incident on the reflecting surface of the mirror. In the case of internal reflection, when the reflecting surface is the mirror output surface, the term 2π is absent in the first expression.

It follows from these expressions that $|E_-(t)|^2 + |E_+(t)|^2 = |E_1(t)|^2 + |E_2(t)|^2$. Assuming that $R = 0.5$ and simplifying the expressions, we arrive at

$$|E_+(t)|^2 = 0.5|E_1(t)|^2 + 0.5|E_2(t)|^2 +$$

$$+\sqrt{|E_1(t)|^2|E_2(t)|^2}\cos[\Delta\varphi(t)],$$

$$|E_-(t)|^2 = 0.5|E_1(t)|^2 + 0.5|E_2(t)|^2$$

$$-\sqrt{|E_1(t)|^2|E_2(t)|^2}\cos[\Delta\varphi(t)].$$

At $|E_1(t)|^2 = |E_2(t)|^2$, we have the following expression for $\Delta\varphi(t)$:

$$\Delta\varphi(t) = \arccos\{[|E_+(t)|^2 - |E_-(t)|^2][|E_+(t)|^2 + |E_-(t)|^2]^{-1}\}.$$

Thus, having compared the pulse shapes measured by high-speed photodiodes [(*13*) and (*15*)], we can find the dependence $\Delta\varphi(t)$. At $R \neq 0.5$ and $|E_1(t)|^2 \neq |E_2(t)|^2$, more complex expressions must be used.

First we used compressed Xe at a pressure $p = 42$ atm as an active medium. In this case, the laser pulse duration was 45 ns (the width of master oscillator pulse P_p in Fig. 3a). Since the acoustic phonon lifetime in compressed Xe is $T_2 = 35$ ns (see Table 1), the condition $\tau_f \leqslant T_2$ is satisfied.

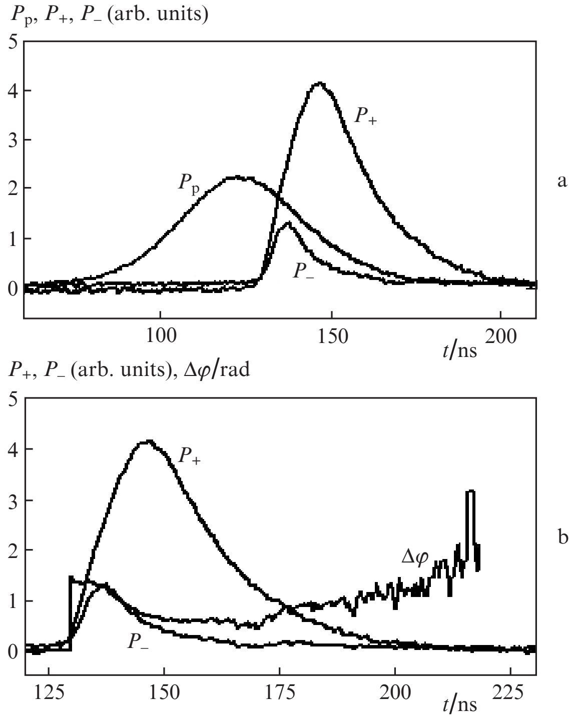

Figure 3. (a) Oscillograms of pump pulse P_p and Stokes pulses P_+ and P_-, corresponding to waves E_+ and E_- in Fig. 2. (b) Oscillograms of Stokes pulses P_+ and P_- (the areas under the pulses are proportional to their energies) and the phase difference $\Delta\varphi$ calculated based on them.

The oscillograms of pulses P_+ and P_- (i.e., $|E_+(t)|^2$ and $|E_-(t)|^2$), recorded by photodiodes (*13*) and (*15*), respectively, and the dependences $\Delta\varphi(t)$ are shown in Fig. 3. In this case, the in-phase parameter $\eta = 157(157 + 32) = 0.83$ (energies are in relative units). The phase difference $\Delta\varphi(t)$ changes during the pump pulse (see Fig. 3b), in view of which the P_- pulse FWHM is smaller. By the end of the pump pulse, fluctuations of the dependence $\Delta\varphi(t)$ grow because the fluctuations of Stokes pulse amplitudes become comparable with their amplitudes. Measurements with a series of pulses (spaced by ~10 min) showed that the in-phase parameter changes in wide limits: $0 < \eta < 1$. In addition, the phase may change during a pulse.

Then we reduced (using nonlinear conversion) the pump pulse leading edge to $\tau_f \approx 10$ ns (P_p in Fig. 4a) and applied Freon FC-75 as an active medium. The in-phase parameter for this series of pulses also changed in wide limits ($\eta \approx 0.4$ for the pulse in Fig. 4). The Stokes pulses P_1 and P_2 emerged from the cell to be recorded by the photodiodes [(*11*) and (*10*)] (Fig. 4b). The significantly different shapes of pulses P_+ and P_- are indicative of a change in the phase difference $\Delta\varphi$ for the pulses (Fig. 4c).

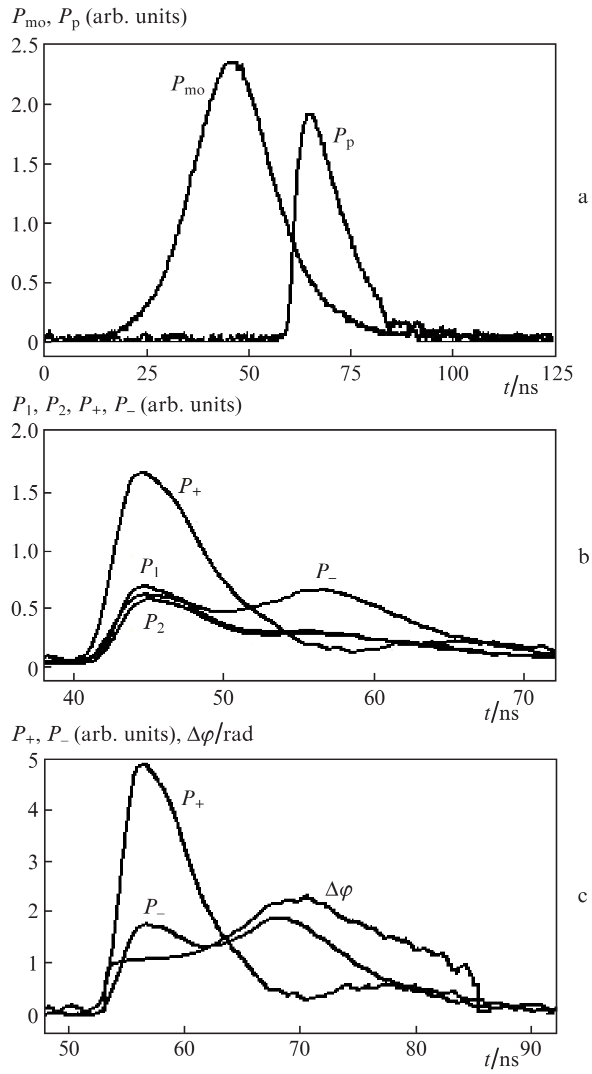

Figure 4. (a) Oscillograms of a master oscillator pulse P_{mo} and SBS mirror pump pulse P_p, (b) Stokes pulses (pulses P_1 and P_2 correspond to waves E_1 and E_2 in Fig. 2) and (c) Stokes pulses P_+ and P_- (the areas under the pulses are proportional to their energies) and the phase difference $\Delta\varphi$ calculated based on them.

Finally, we used an electro-optic shutter (Pockels cell) to shorten the pump pulse leading edge to $\tau_f \leqslant 2$ ns (Fig. 5a); the active medium was, as previously, FC-75. Under these conditions, the in-phase parameter also varied from pulse to pulse in wide limits ($\eta \approx 0.3$ for the pulse in Fig. 5), and phase difference $\Delta\varphi$ changed during a pulse (Fig. 5c).

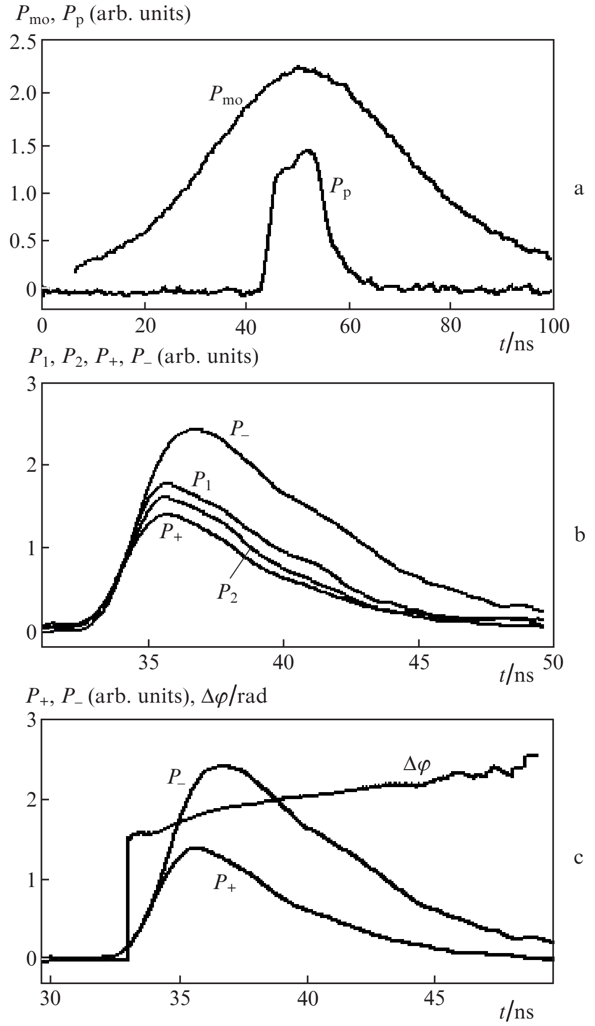

Figure 5. (a) Oscillograms of a master oscillator pulse P_{mo} and SBS mirror pump pulse P_p, (b) Stokes pulses, and (c) Stokes pulses P_+ and P_- (the areas under the pulses are proportional to their energies) and the phase difference $\Delta\varphi$ calculated based on them.

These results show that the phasing scheme for two independent channels with SBS mirrors is in essence a classical Michelson interferometer. The phase difference of Stokes waves for the backward summation on the beam-splitting mirror (*6*) is determined by the expression $\Delta\varphi = k\Delta l$, where k is the wave number and Δl is the optical difference in the interferometer arm lengths. Therefore, to form a stable interference pattern, one must maintain the Δl value constant accurate to few tenths of the light wavelength. This requirement is absolutely unrealistic for high-power laser systems. In our setup, the interferometer arm lengths were ~2 m. The optical scheme was assembled on a conventional laboratory table, without any thermal stabilisation. In addition, there was a mechanical effect of the power circuits of pulse-discharge pump lamps (discharge pulse width ~10^{-3} s) on the optical table. Therefore, the drift of different optical elements and fluctuations of the refractive index of air caused significant fluctuations of Δl from pulse to pulse. This, in its turn, led to random energy splitting on the mirror (*6*).

An analysis of the above results shows the following. To obtain stable wave interference on a beam-splitting mirror under conventional laboratory conditions, one must modify the scheme so as to provide automatic compensation for Δl fluctuations. A modified version is presented in Fig. 6. It contains the same measuring elements as the scheme in Fig. 2. The difference is that the beams from two channels are introduced into the cell from the same side at a small angle, so as to make them cross beyond the cell. A spherical mirror is installed at the beam intersection point, so that its optical axis is codirectional with the angle bisector of the beam convergence angle. Thus, the spherical mirror focuses each beam not in the direction opposite to it but in the direction opposite to the other beam. Let us show that this scheme implements the following important property: for the cases of both external and internal reflection, the differences in the optical path lengths from the semitransparent mirror to the interference plane are $n\lambda_p$ (n is an integer) in both arms at any longitudinal displacements of the reflecting elements of the interferometer. In contrast to the scheme used in [6–9], where phase conjugation mirrors were located in independent interferometer arms, the phase conjugation mirrors in the version considered above are coupled.

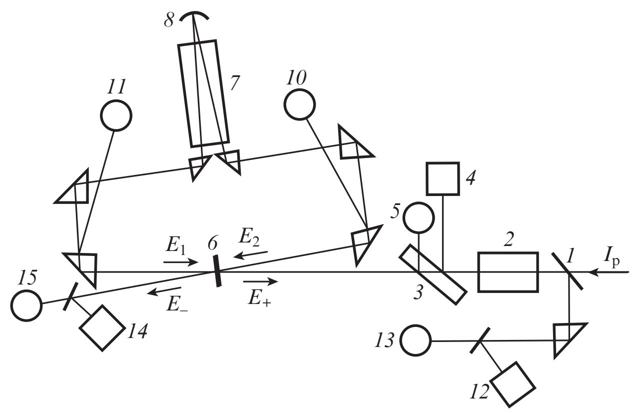

Figure 6. Schematic diagram of the modified experimental setup (see Fig. 2), in which the concave mirror (*8*) inside the cell (*7*) focuses each pump beam towards the other one.

Impact SBS excitation is performed by waves passed through different arms of the interferometer. In sum, the phase difference of reflected waves on the beam-splitting mirror (*6*) is given by the expression $\Delta\varphi = \Delta k\Delta l$, where $\Delta k = |k_p| - |k_S|$; and k_p and k_S are the wave numbers of the pump and Stokes waves, respectively. Under SBS conditions, $\Delta k \approx 2kv_s/c$, where v_s is the speed of sound and c is the speed of light. Therefore, $\Delta k \sim (10^{-6} - 10^{-5})k$ for most of SBS media. Hence, to obtain stable interference on the beam-splitting mirror (*6*), it is sufficient to maintain Δl constant accurate to several tenths of centimetre.

Experiments in the scheme with coupled SBS mirrors demonstrated stable interference on the beam-splitting mirror (*6*); thus, radiation constantly arrived at the same measurement channel (E_+), and the in-phase parameter η was ~0.93 ± 0.02 [for pump pulses with durations of ~10 ns (Fig. 7) and ~40 ns (Fig. 8) and steep leading edges]. The phase difference remained constant during the pulse.

To obtain a direct experimental proof of the impact mechanism of wave phasing under SBS conditions, we performed additional experiments with long (FWHM ~45 ns) pump pulses (P_p in Fig. 3a), i.e., with pulses having flat leading edges. The following results were obtained: phasing of Stokes beams was absent in all experiments, and the phase differ-

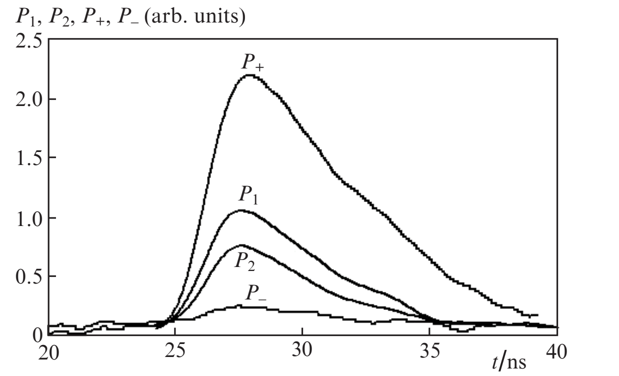

Figure 7. Oscillograms of Stokes pulses in the scheme with coupled SBS mirrors and a high in-phase parameter ($\eta \approx 0.93$). The areas under pulses P_+ and P_- are not proportional to their energies. The shape of the pump pulse is shown in Fig. 5a.

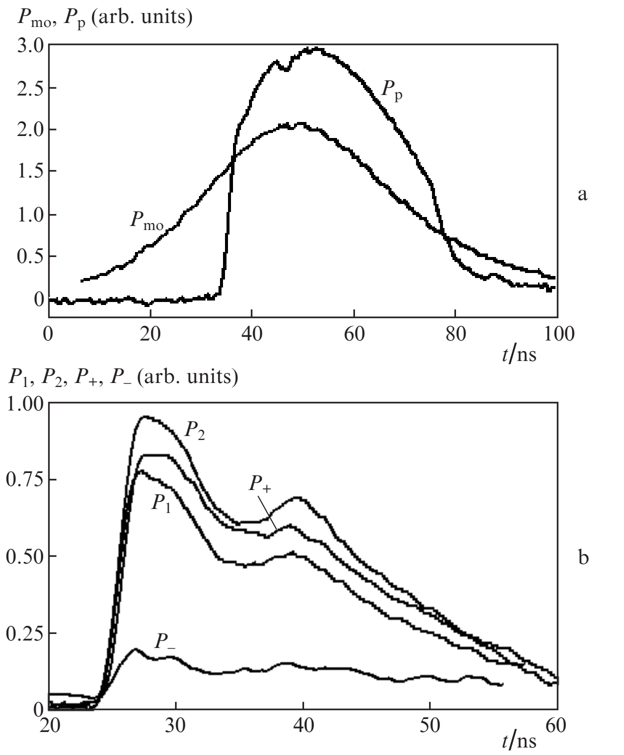

Figure 8. Oscillograms of pulses in the scheme with coupled SBS mirrors: (a) master oscillator pulse P_{mo} and pump pulse P_p and (b) Stokes pulses (the areas under pulses P_+ and P_- are not proportional to their energies) in the experiment with a high in-phase parameter ($\eta \approx 0.93$).

ence could change during the pulse. The consequences are as follows. First, pulses with steep leading edges must obviously be used. Second, the interferometric scheme with independent SBS mirrors, proposed in [7–9], is valid for only pulses 1–100 ns long with steep leading edges.

Thus, the results of our study showed the following. Phasing of waves under impact SBS excitation by counterpropagating pump waves is an interesting physical effect. Several strict conditions must be fulfilled to implement it. First, the laser pulse must have a sufficiently steep leading edge (specifically for this reason the SBS excitation was referred to as impact). Second, one must provide very high stability of positioning optical elements of the scheme, so as to maintain the optical difference in the interferometer arm lengths accurate to several tenths of the light wavelength. Finally, the effect is based on the interference of counterpropagating plane waves. Therefore, the issue of phasing of spatially inhomogeneous laser beams calls for a special analysis. The above requirements cannot be satisfied for high-power laser systems. The possibility of phasing only two channels according to the scheme proposed by us does not have any advantages over other existing methods.

In our previous studies [4, 5] we proposed methods for phasing several laser channels, which are free of all aforementioned drawbacks and can be applied to high-power laser systems. These schemes can operate with pulses having any leading edge widths; the only thing to do is to maintain the optical difference in the interferometer arm lengths constant accurate to several tenths of centimetre. These methods are based on phase conjugation of spatially inhomogeneous radiation, which provides compensation for the phase distortions of the amplified signals propagating in the backward direction. Moreover, phasing of nine channels has already been experimentally performed.

References

1. Bourderionnet J., Bellinger C., Primot J., Brignon A. *Opt. Express*, **19** (18), 17053 (2011).
2. Pyrkov Yu.N., Trikshev A.I., Tsvetkov V.B. *Kvantovaya Elektron.*, **42** (9), 780 (2012) [*Quantum Electron.*, **42** (9), 780 (2012)].
3. Volkov M.V., Garanin S.G., Dolgopolov Yu.V., Kapalkin A.V., Kulikov S.M., Sinyavin D.N., Starikov F.A., Sukharev S.A., Tyutin S.V., Khokhlov S.V., Chaparin D.A. *Kvantovaya Elektron.*, **44** (11), 1039 (2014) [*Quantum Electron.*, **44** (11), 1039 (2014)].
4. Basov N.G., Zubarev I.G., Mironov A.B., Mikhailov S.I., Okulov A.Yu. *Zh. Eksp. Teor. Fiz.*, **79** (5(11)), 1678 (1980).
5. Basov N.G., Efimkov V.F., Zubarev I.G., Kotov A.V., Mikhailov S.I. *Kvantovaya Elektron.*, **8** (10), 2191 (1981) [*Sov. J. Quantum Electron.*, **11** (10), 1335 (1981)].
6. Lee S.K., Kong H.J., Nakatsuka M. *Appl. Phys. Lett.*, **87** (16), 161109 (3) (2005).
7. Kong H.J., Yoon J.W., Lee O.W., Lee S.K., Nakatsuka M. *J. Korean Phys. Soc.*, **49**, S39 (2006).
8. Kong H.J. *Proc. 3rd Int. Conf. on the Frontiers of Plasma Physics and Technology (PC/5099)* (Daejon, Korea, 2007) pp S7-1–S7-43.
9. Kong H.J., Lee S.K., Yoon J.W., Shin J.S., Park S. *Advances in Laser and Electro Optics* (Rijeka, Croatia: INTECH, 2010) p. 838.
10. Gordeev A.A., Efimkov V.F., Zubarev I.G., Mikhailov S.I. *Kvantovaya Elektron.*, **41** (11), 997 (2011) [*Quantum Electron.*, **41** (11), 997 (2011)].